# SURFACE FATIGUE EVALUATION OF GEAR MATERIALS AND LUBRICANTS

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Summary

The surface fatigue life of several gear materials, gear processes and gear lubricants were evaluated in the NASA spur gear fatigue test rig during the last several years. Some of these materials include VIM-VAR AISI 9310, EX-53, CBS-1000M, CBS-600, VASCO-X2 , M50-Nil, VASCO Matrix II, VASCO Max 350, and Nitralloy N. Some of the various processes include shot peening at different intensities and hot forged powder metal AISI 4620. Several aircraft gear lubricants with different viscosity's and additives were evaluated for their effect on surface fatigue of standard spur gears. These materials and lubricants were evaluated for possible use in aircraft gear applications. The fatigue life of the gear materials and lubricants were compared with the life of the standard AISI 9310 aircraft gear material and the NASA base lubricant. Surface fatigue tests were conducted at a lubricant inlet temperature of 321K (120° F), a lubricant outlet temperature of 350K (170° F), a maximum Hertz stress of 1.71 GPa (248ksi) and a speed of 10000 rpm.

## Introduction

Aircraft turbine engine requirements are increasing the demand for higher reliability and higher operating temperature in many advanced and high power density applications for gears and rolling element bearings. The surface temperature of power gearing normally operates considerably higher than the bulk oil temperature; thereby, requiring improved lubricants and gear material that will provide long life at increased operating temperature.. Previous testing with rolling element bearings has shown that at high stress loads the surface fatigue life of bearings is much longer when the surface hardness at the operating temperature is Rockwell Rc 58 or higher and is drastically reduced when the hardness is less than Rc 58.

The objective of the research work reported in this paper was to compare under closely controlled test conditions the fatigue lives and failure modes of test spur gears made of advanced materials or improved material processing and the fatigue lives of standard test gears using advanced gear lubricants and compare the results with the standard aircraft gear material AISI 9310 using standard lubricants.

## Test Gears, Materials and Lubricants

The test gears used in the tests reported herein are shown in figure 2. Dimensions for the test gears are summarized in table I. All gears had a minimal surface finish on the tooth flank of 0.406 μ m cla (16 μ in cla) and a standard 20° involute tooth profile with a small profile tip relief.

The standard test gears were manufactured from AISI 9310. Two sets of standard test gears were shot peened at different intensities. The other gear materials tested were VIM-VAR AISI 9310, EX-53, CBS-600, CBS 1000M, M50-Nil, Vasco max 350, Vasco matrix II, Vasco X-2, Nitralloy N and hot forged powder metal AISI 4620. Table II is a list of the chemical composition of the materials discussed in this report. Most of the gears were case carburized and hardened, however the Vasco max 350 and matrix II were through hardened and the nitralloy N was nitrided. All the test gears had a nominal surface hardness of Rc 60.

Seven lubricants were selected for surface fatigue endurance tests with the CVM AISI 9310 steel gear test specimens. Lubricant properties are given in table III and include an unformulated base stock lubricant with no lubricant additives, a 5 cSt lubricant meeting the MIL-L-23699 specification, a lubricant meeting the MIL-L-7808J specification, a 5 cSt lubricant developed for helicopter gearboxes under the specification DOD-L-85734, a 7.5 cSt lubricant with an anti wear additive package meeting a special development specification DERD-2487, and two 9 cSt ester based lubricants with and without an additive package. Six of the seven lubricants could be classified as synthetic polyol-ester base stock lubricants while lubricant E is a polyalkylene-glycol with a small amount of boundary lubrication additive.

## Apparatus, and Procedure

### Gear Test Apparatus

The gear fatigue tests were performed in the NASA Lewis Research Center's gear test apparatus. A schematic of the test rig is shown in figure 1. Oil pressure and leakage flow are supplied to the load vanes through a shaft seal. The two identical test gears can be started under no load, and the load can be applied gradually, without changing the running track on the gear teeth.

Separate lubrication systems are provided for the test gears and the main gearbox.. The test gear lubricant is filtered through a 5-μm-nominal fiberglass filter.

A vibration transducer mounted on the gearbox is used to automatically shut off the test rig when a gear surface fatigue occurs. The gearbox is also automatically shut off if there is a loss of oil flow to either the main gearbox or the test gears, if the test gear oil overheats, or if there is a loss of seal gas pressurization. The operating speed for the test reported herein was 10,000 rpm.

### Test Procedure

After the test gears were cleaned to remove the preservative, they were assembled on the test rig. The 0.635-cm (0.25-in.) wide test gears were run in an offset condition with a 0.30-cm (0.12-in.) tooth-surface overlap to give a load surface on the gear face of 0.28 cm (0.11 in.), thereby allowing for the edge radius of the gear teeth. All tests were run in at a pitch-line load of 1225 N/cm (700 lb/in) for 1 hour, which gave a maximum Hertz stress of 0.756 GPa (111 ksi). The load was then increased to 5784 N/cm (3305 lb/in), which gave a pitch-line maximum Hertz stress of 1.71 GPa (248 ksi) and a bending stress of 0.26 Gpa (37 ksi).

Operating the test gears at 10 000 rpm gave a pitch-line velocity of 46.55 m/sec (9163 ft/min). Lubricant was supplied to the inlet mesh at 800 $cm^3$/min (0.21 gpm) at 321K (120° F). The lubricant outlet temperature was nearly constant at 350 K (170° F).

The pitch-line elastohydrodynamic (EHD) film thickness was calculated by the Dawson and Higginson method. The EHD film thickness for the gear materials test conditions was computed to be 0.33 m (13 in.), which gave an $h/\sigma$ of 0.55. The EHD film thickness for the lubricant tests are given in table III.

## Conclusions

There were 13 different gear material tests and seven different lubricant tests reported in this study. Nine of the materials tested had surface fatigue lives that were greater than the standard test gears. Four of these materials had surface fatigue lives that were several times the standard test gears with the M50-Nil having a fatigue life more than ten times the standard gears. The lubricant test demonstrated that the surface fatigue life of standard gears can be increased approximately ten times by a lubricant that has a good additive package and provides an EHD film thickness with an $h/\sigma$ greater than one.

## References


1. Townsend, Dennis P. and Zaretsky, E. V. "Endurance and Failure Characteristics of Modified Vasco X-2, CBS 600 and AISI 9310 Spur Gears" NASA TM 81421 Aug. 1980
2. Townsend, Dennis P. and Zaretsky, Erwin V. "Effrects of Shot Peening on Surface Fatigue Life of Carburized and Hardened AISI 9310 Spur Gears" NASA TP 2047 Aug. 1982
3. Townsend, Dennis P. " Surface Fatigue Life and Failure Characteristics of EX-53, CBS 1000M, and AISI 9310 Gear Materials". NASA TP 2513 Oct. 1985
4. Townsend, Dennis P. "Surface Fatigue and Failure Characteristics of Hot Forged Powder Metal AISI 4620, AISI 4640, and Machined AISI 4340 Steel Spur Gears". NASA TM 87330 May 1986.
5. Townsend, D. P. and Bamberger, E. N. "Surface Fatigue Life of M50NiL and AISI 9310 Gears and Roling-Contact Bars". AIAA Journal of Propulsion and Power, Vol. 7, NO 4, July 1991 pp 642-649.
6. Townsend, Dennis P. "Improvement in Surface Fatigue Life of Hardened Gears by High-Intensity Shot Peening". NASA TM 105678, AVSCOM TR 91-C-042 Sept 1992.
7. Townsend, Dennis P. "Surface Fatigue Life of High Temperature Gear Materials". NASA TM 106562, AVSCOM TR ARL-TR-401 June 1994
8. Townsend, Dennis P. and Shimski, John "Evaluation of the EHL Film Thickness and Extreme Pressure Additives on Gear Surface Fatigue Life". NASA TM 106663, ARL TR ARL-TR-477 Dec. 1994

## NASA Lewis Research Center's Gear Fatigue Test Apparatus

### Gearbox

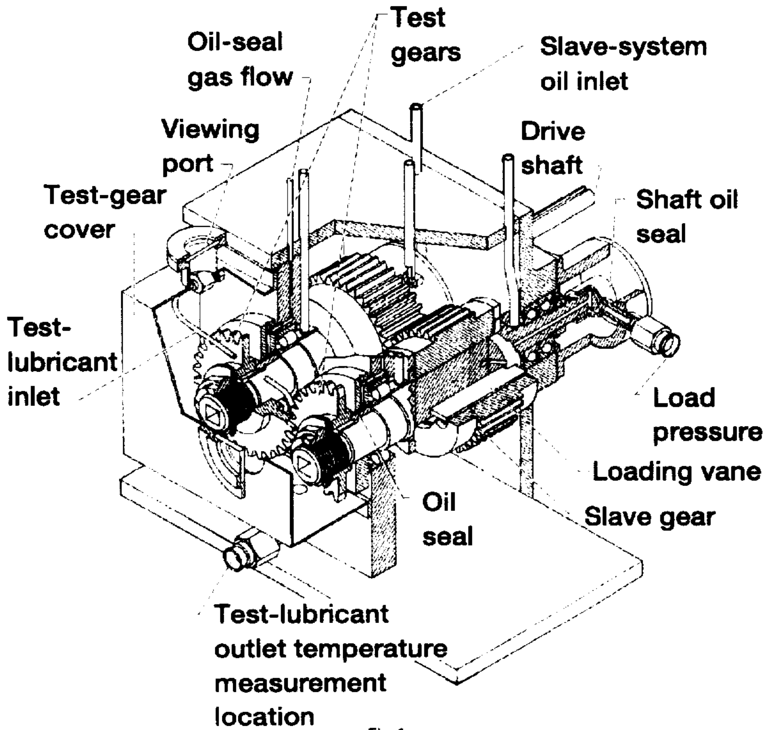



Fig. 1a

## NASA Lewis Research Center's Gear Fatigue Test Apparatus

### Schematic

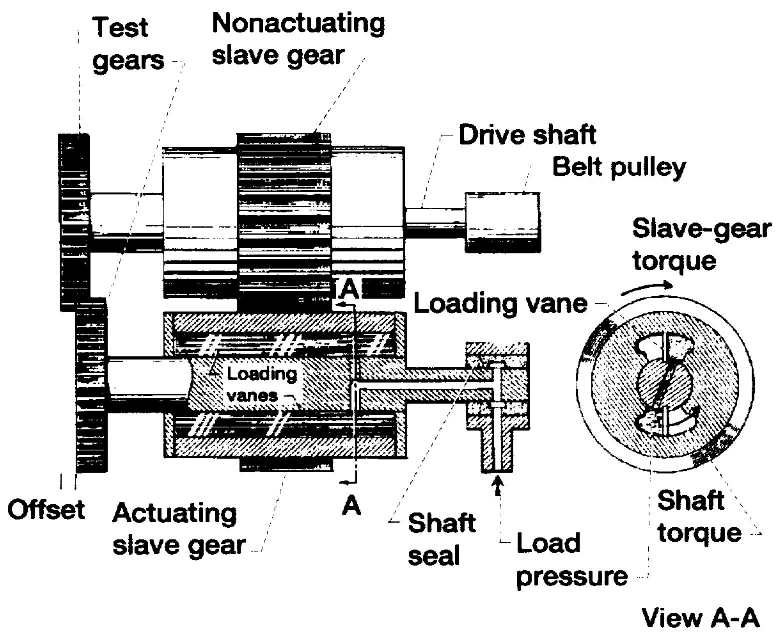
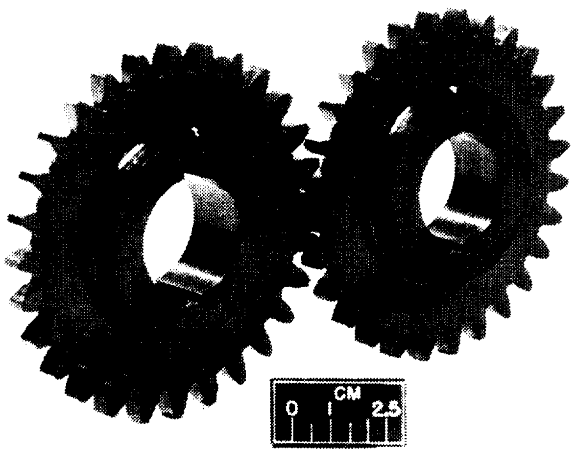



Fig. 1b

# Test-Gear Configuration




## Spur Gear Data

[Gear tolerance per AGMA class 12.]

| | |
|---|---|
| Number of teeth | 28 |
| Diametral pitch | 8 |
| Circular pitch, cm (in.) | 0.9975 (0.3297) |
| Whole depth, cm (in.) | 0.762 (0.300) |
| Addendum, cm (in.) | 0.318 (0.125) |
| Chordal tooth thickness (reference), cm (in.) | 0.485 (0.191) |
| Tooth width, cm (in.) | 0.635 (0.25) |
| Pressure angle, deg | 20 |
| Pitch diameter, cm (in.) | 8.890 (3.500) |
| Outside diameter, cm (in.) | 9.525 (3.750) |
| Root fillet, cm (in.) | 0.102 to 0.152 (0.04 to 0.06) |
| Measurement over pins, cm (in.) | 9.603 to 9.630 (3.7807 to 3.7915) |
| Pin diameter, cm (in.) | 0.549 (0.216) |
| Backlash reference, cm (in.) | 0.0254 (0.010) |
| Tip relief, cm (in.) | 0.001 to 0.0015 (0.0004 to 0.0006) |

Fig. 2

# Nominal Chemical Composition of Gear Materials

| ELEMENT | AISI9310 | VASCO Matrix II | VASCO Max 350 | Nitralloy N | EX-53 | CBS 600 | CBS 1000 | VASCO X-2 | M50-NiL | AISI 4620 |
|---|---|---|---|---|---|---|---|---|---|---|
| Carbon | 0.1 | 0.51 | 0.01 | 0.24 | 0.01 | 0.19 | 0.14 | 0.14 | 0.13 | 0.11 |
| Nickel | 3.22 | – | 18.5 | 3.5 | 2.13 | 0.18 | 2.94 | 0.1 | 3.44 | 1.82 |
| Chromium | 1.21 | 4.0 | – | 1.18 | 1.05 | 1.5 | 1.12 | 4.9 | 4.21 | – |
| Molybdenum | 0.12 | 5.0 | 4.8 | 0.25 | 3.3 | 0.95 | 4.77 | 1.36 | 4.3 | 0.4 |
| Cobalt | – | 8.0 | 12.0 | – | – | – | – | 0.02 | 0.01 | – |
| Manganese | 0.63 | 0.15 | 0.05 | 0.55 | 0.37 | 0.61 | 0.48 | 0.25 | 0.28 | 0.25 |
| Silicon | 0.27 | 0.2 | 0.05 | 0.3 | 0.98 | 1.05 | 0.43 | 0.91 | 0.18 | 0.03 |
| Sulfur | 0.005 | 0.03 | 0.01 | 0.03 | 0.006 | 0.01 | 0.019 | 0.01 | 0.002 | 0.03 |
| Phosphorous | 0.005 | 0.03 | 0.01 | 0.03 | 0.009 | 0.01 | 0.018 | 0.01 | 0.002 | 0.03 |
| Aluminum | – | – | 0.1 | 1.08 | – | – | – | – | – | – |
| Copper | 0.13 | – | – | – | 2.07 | – | – | 0.07 | 0.05 | – |
| Tungsten | – | 1.0 | – | – | – | – | – | 1.35 | – | – |
| Vanadium | – | 1.0 | – | – | 0.12 | – | 0.1 | 0.42 | 1.19 | – |
| Titanium | – | – | 1.40 | – | – | – | – | – | – | – |
| Boron | – | – | 0.003 | – | – | – | – | – | – | – |
| Calcium | – | – | 0.05 | – | – | – | – | – | – | – |
| Zirconium | – | – | 0.02 | – | – | – | – | – | – | – |
| Iron | Bal. | Bal. | Bal. | Bal. | Bal | Bal | Bal | Bal | Bal | Bal |

Fig. 3

## Typical Fatigue Spalls and Cross Section of Test Gears

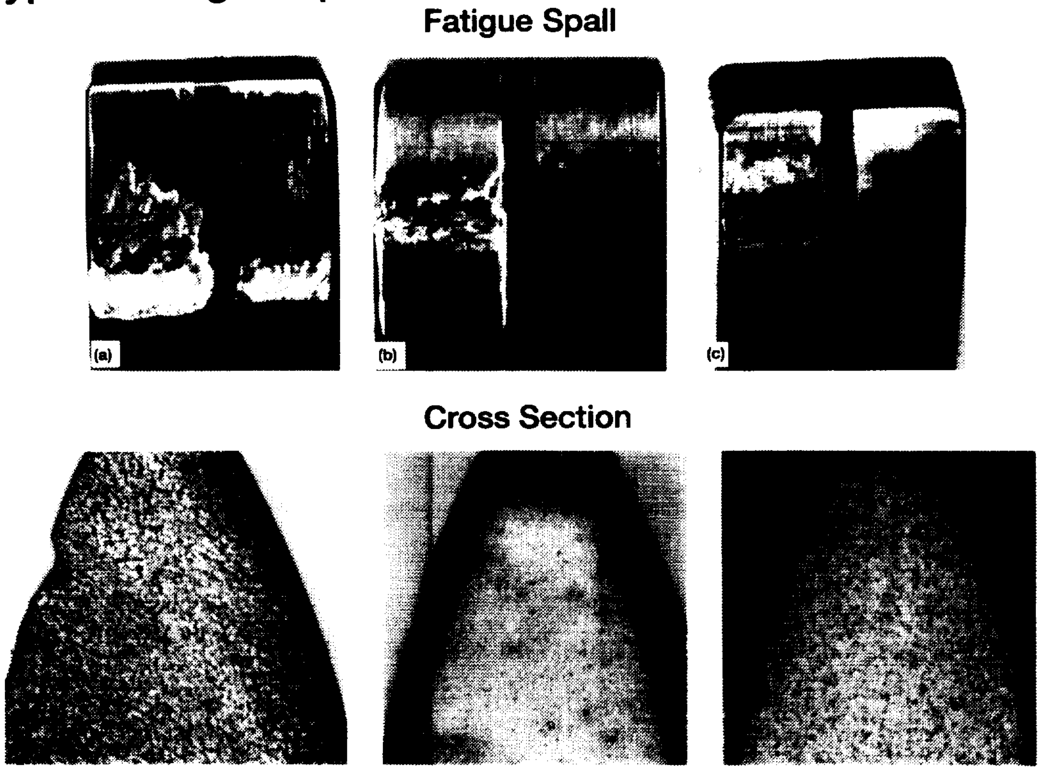



Fig. 4

## Surface Fatigue Life of CBS 600

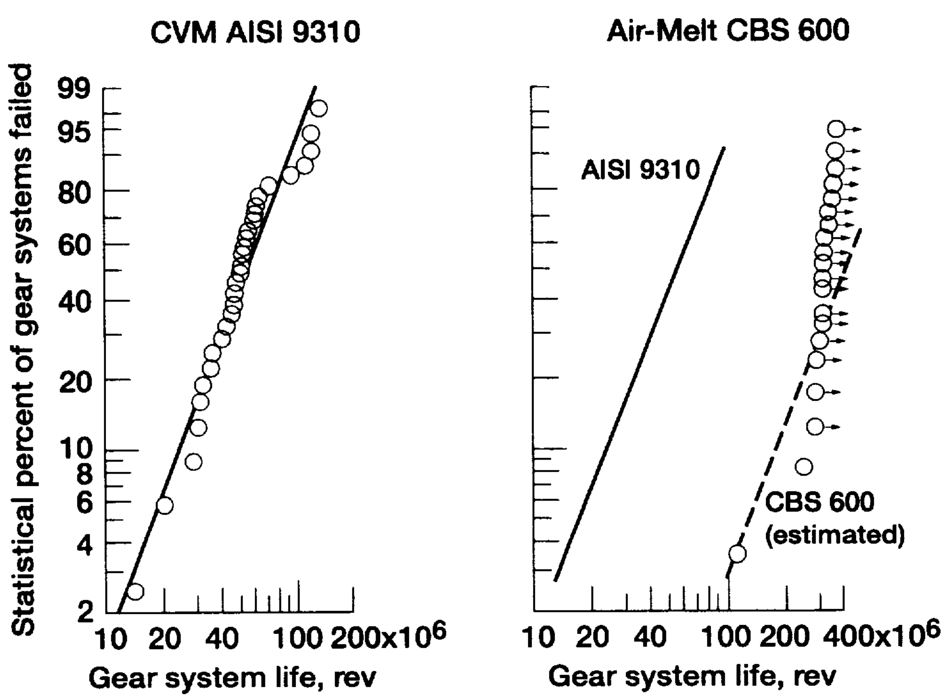



Fig. 5

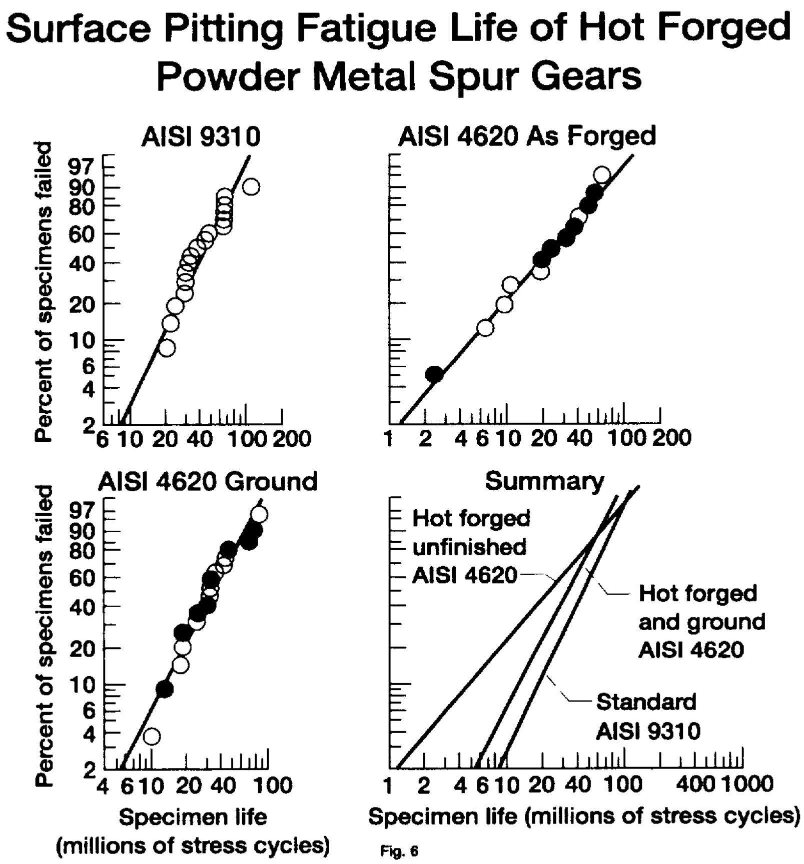

Surface Pitting Fatigue Life of Hot Forged Powder Metal Spur Gears
AISI 9310
AISI 4620 As Forged
AISI 4620 Ground
Summary
Percent of specimens failed
97
90
80
60
40
20
10
6
4
2
6 10 20 40 100 200
1 2 4 6 10 20 40 100 200
4 6 10 20 40 100
1 2 4 6 10 20 40 100 400 1000
Hot forged unfinished AISI 4620
Hot forged and ground AISI 4620
Standard AISI 9310
Specimen life (millions of stress cycles)

Fig. 6

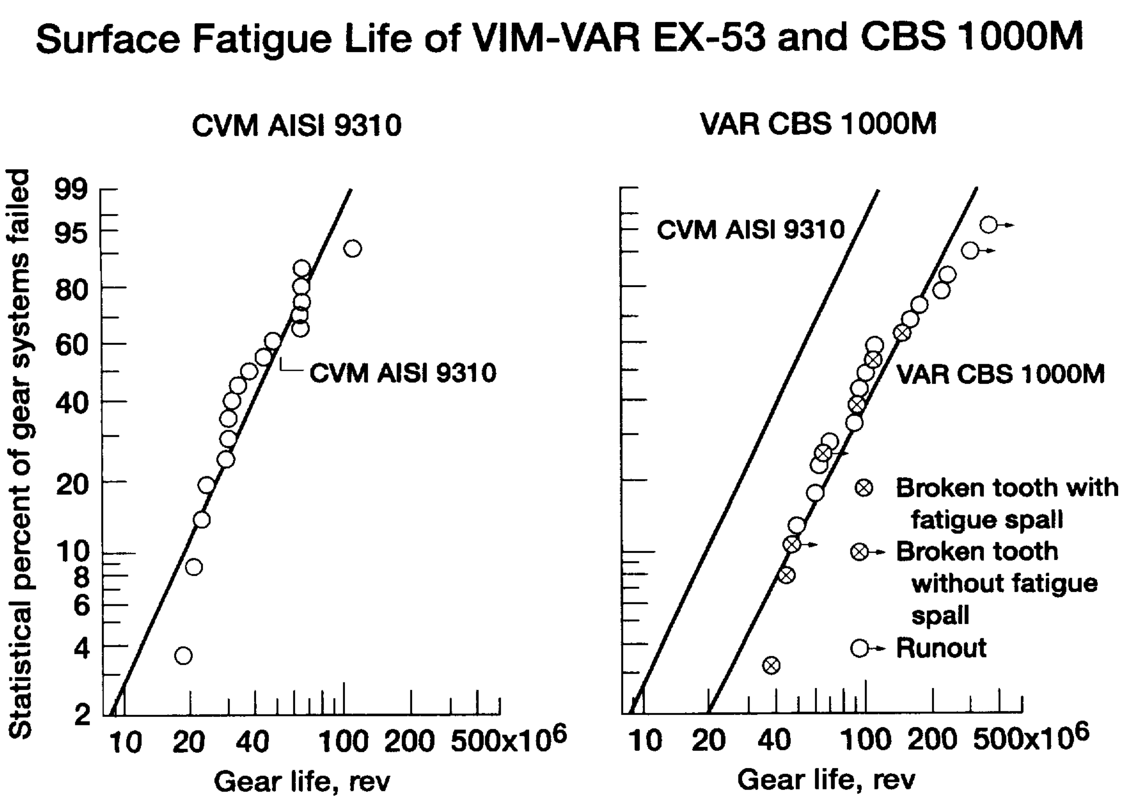

Surface Fatigue Life of VIM-VAR EX-53 and CBS 1000M
CVM AISI 9310
VAR CBS 1000M
Statistical percent of gear systems failed
99
95
80
60
40
20
10
8
6
4
2
10 20 40 100 200 500x10⁶
Gear life, rev
CVM AISI 9310
VAR CBS 1000M
Broken tooth with fatigue spall
Broken tooth without fatigue spall
Runout

Fig. 7a

## Surface Fatigue Life of VIM-VAR EX-53 and CBS 1000M

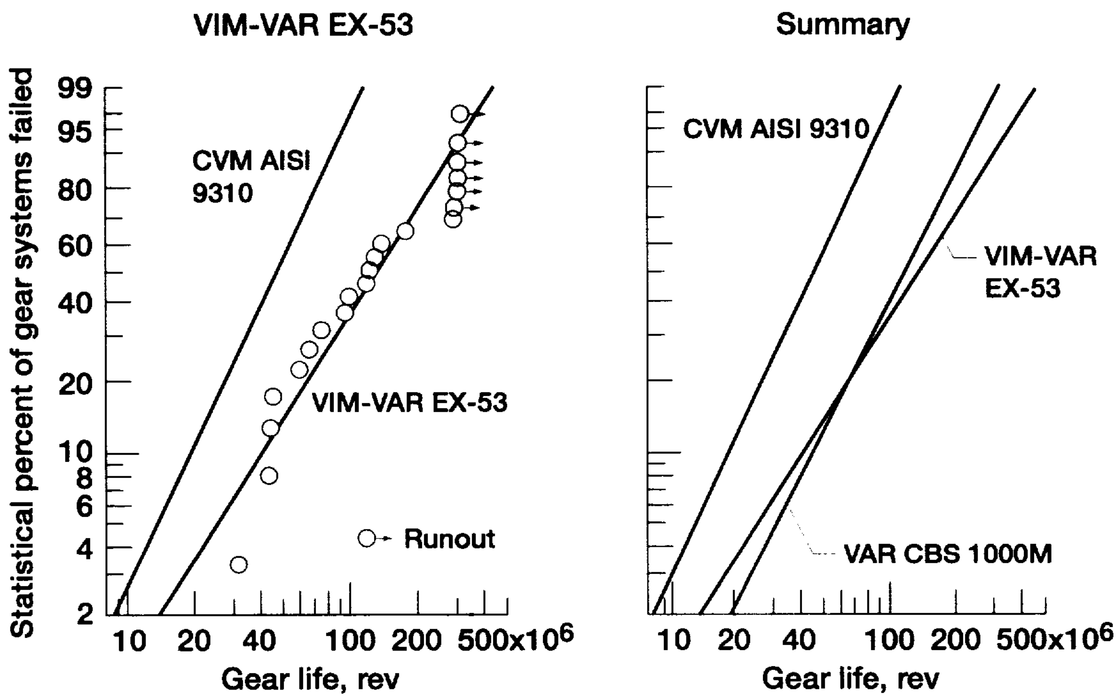



Fig. 7b

## End View of Shot Peened Gears

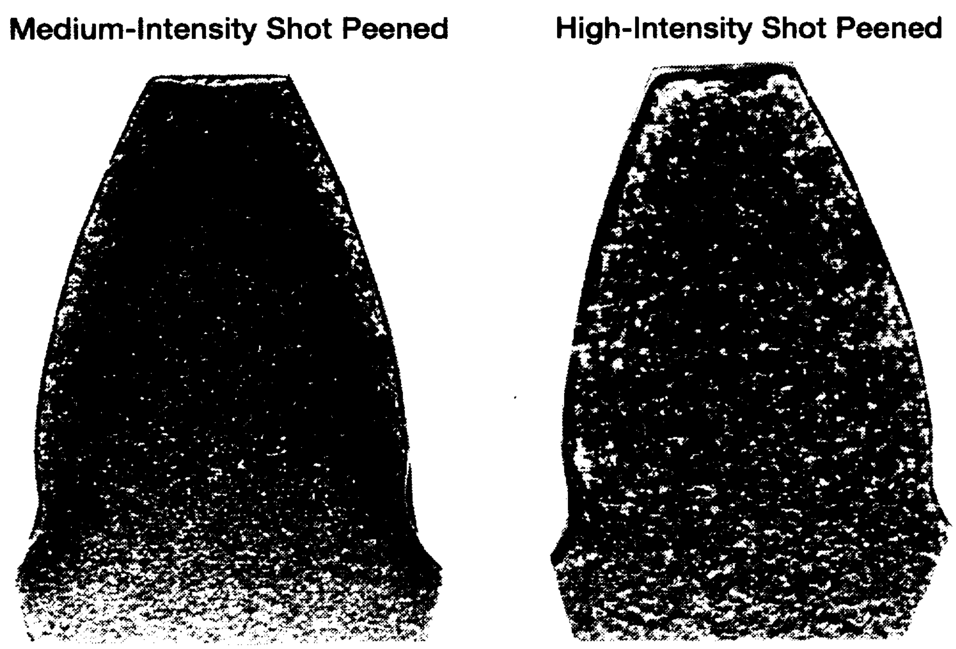



Fig. 8

## Measure of Subsurface Residual Stress of Gear Tooth

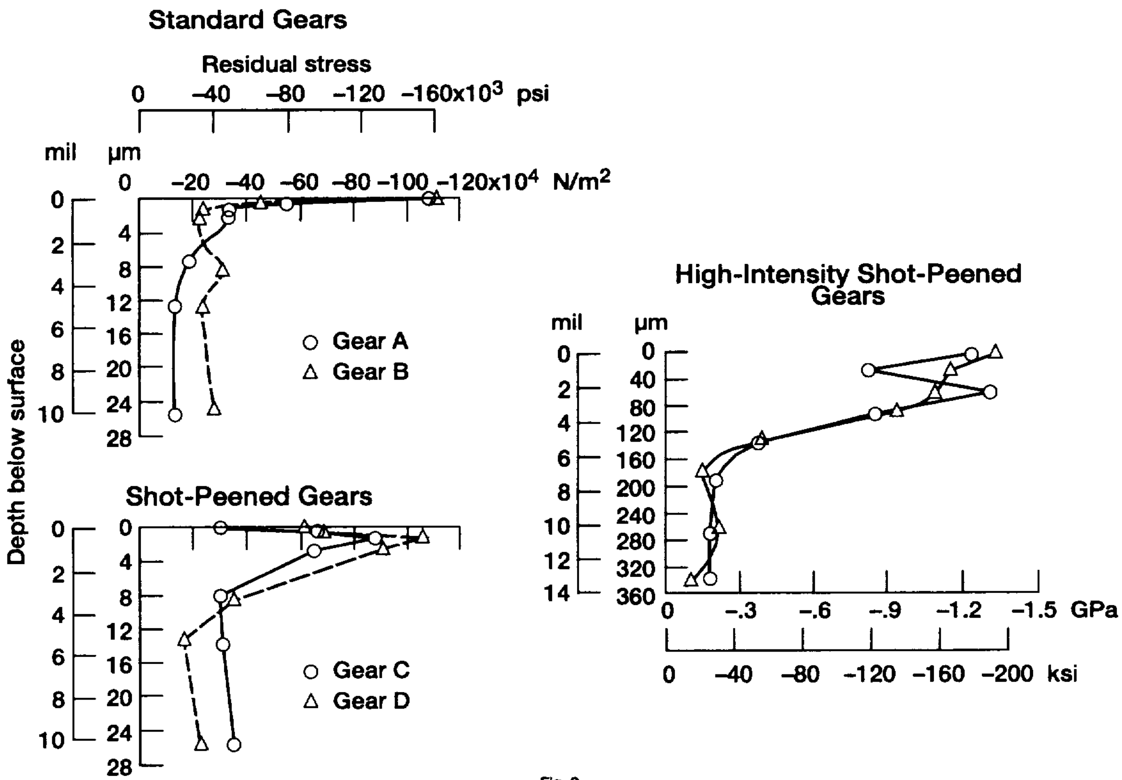



Fig. 9

## Surface Fatigue Life of Shot Peened Gears

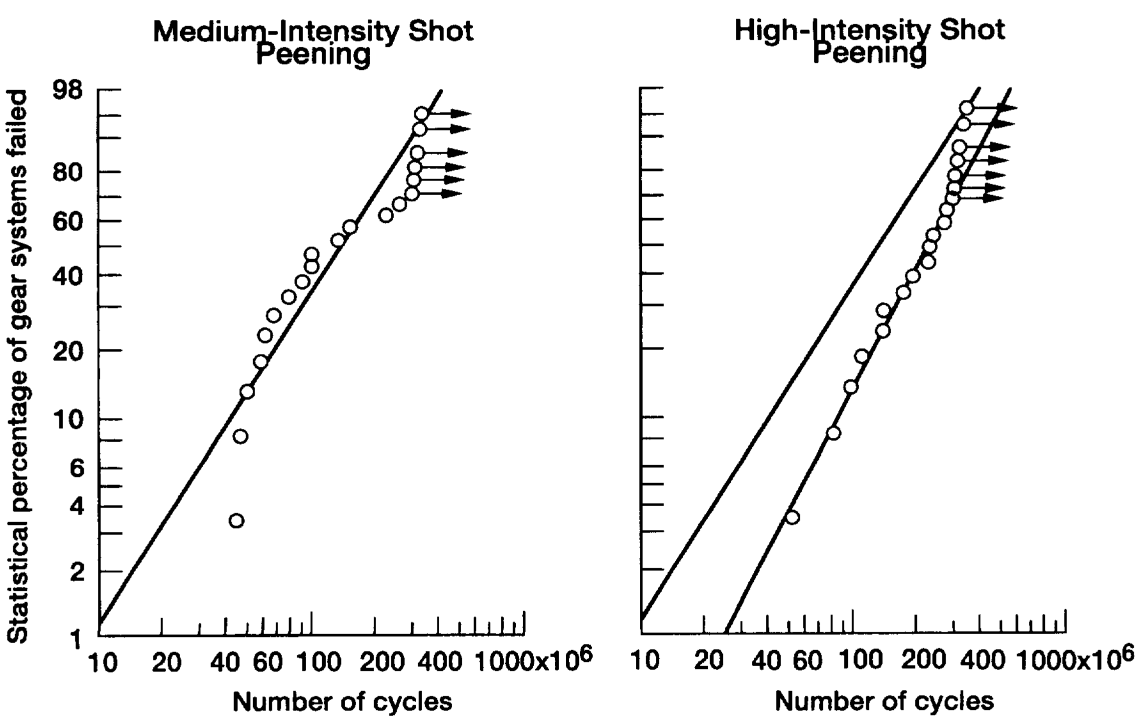



Fig. 10

## Surface Fatigue Life of VASCO X-2

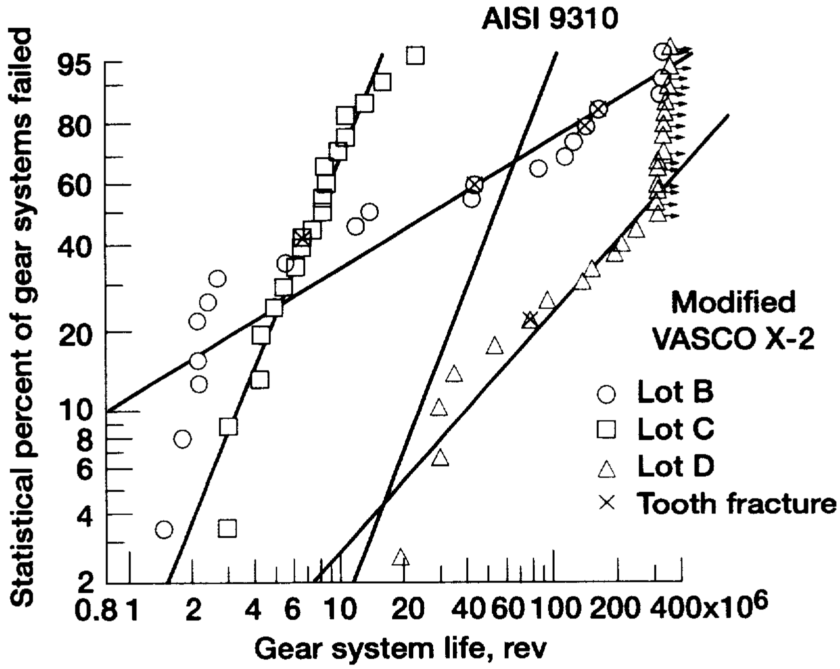



Fig. 11

## Surface Fatigue Life of High-Temperature Steels

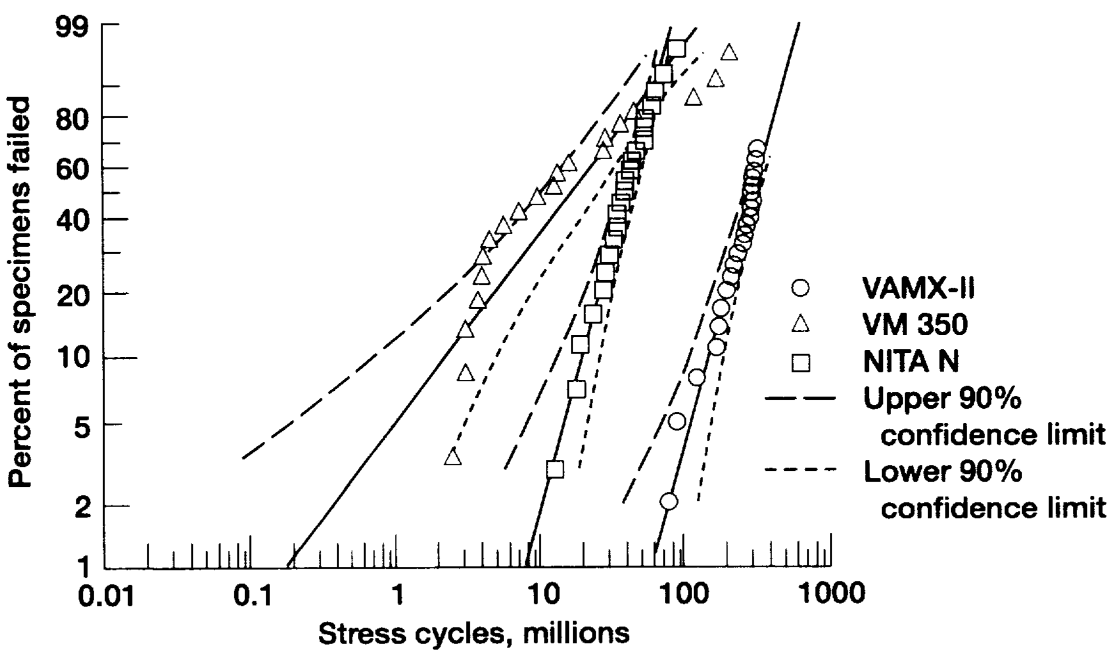



Fig. 12

## Surface Fatigue Life of 9310 and M50 NiL

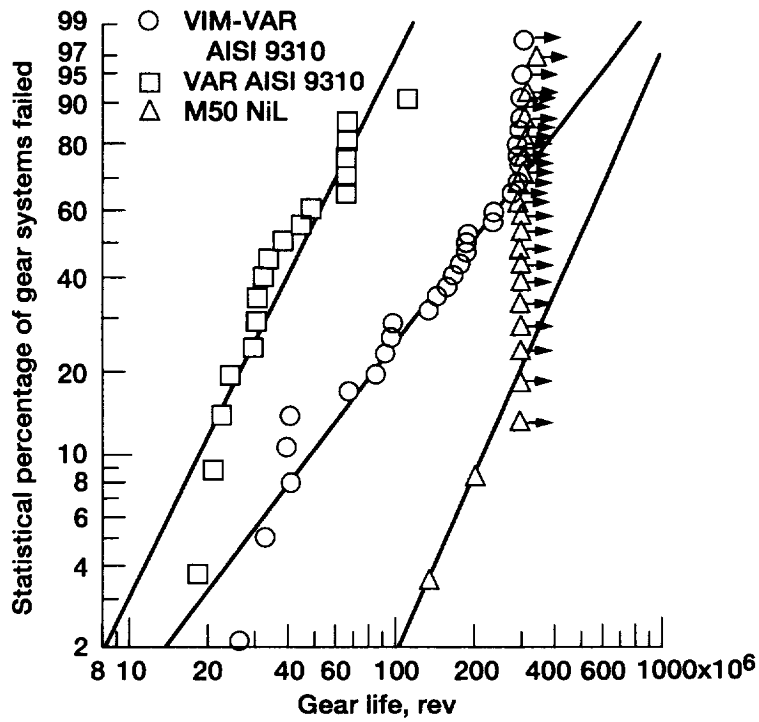



Fig. 13

## Surface Pitting Fatigue Lives of AISI 9310 With Different Lubricants

| Lubricant code NASA | Lubricant basestock | Gear system life, millions of stress cycles 10 percent | 50 percent | Weibull slope | Failure index[a] | Confidence number,[b] percent |
|---|---|---|---|---|---|---|
| A | polyol-ester | 5.1 | 20.4 | 1.36 | 30 of 30 | --- |
| B | polyol-ester | 12.1 | 76 | 1.02 | 20 of 20 | 84 |
| C | polyol-ester | 5.7 | 20.7 | 1.46 | 20 of 20 | 55 |
| D | polyol-ester | 11.8 | 50.8 | 1.29 | 17 of 20 | 83 |
| E | polyalkylene-glycol | 46.5 | 152 | 1.59 | 15 of 19 | 99 |
| F | polyol-ester | 45.2 | 276 | 1.04 | 7 of 17 | 99 |
| G | polyol-ester | 103 | 568 | 1.1 | 5 of 18 | 99 |

[a] Number of failures out of number of tests.
[b] Percent of time that 10 percent life obtained with each lubricant will have the same relation to the 10 percent life of lubricant NASA A.

Fig. 14

## Surface Pitting Fatigue Lives of AISI 9310 Gears Run With Seven Different Lubricants

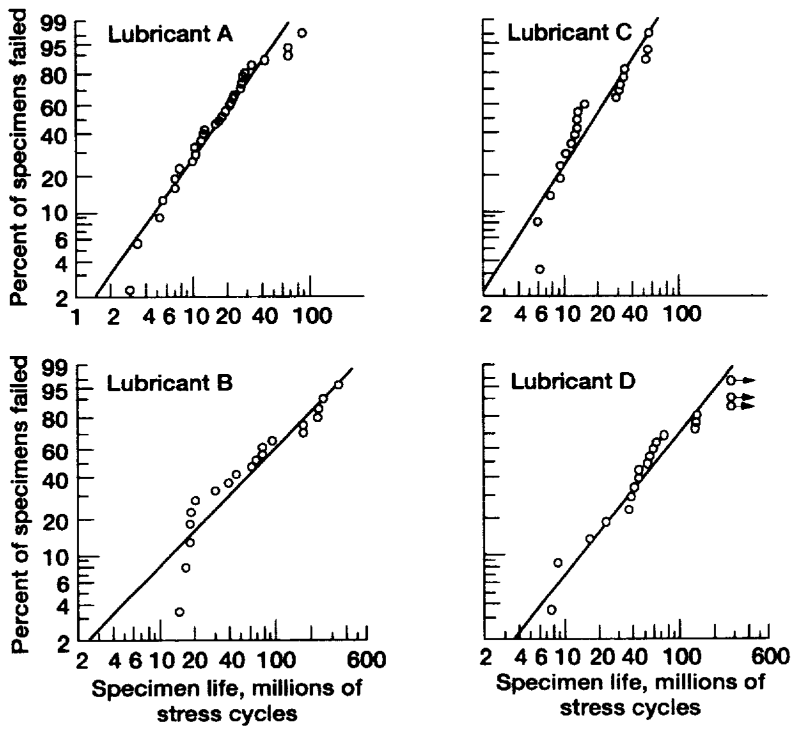



Fig. 15a

## Surface Pitting Fatigue Lives of AISI 9310 Gears Run With Seven Different Lubricants

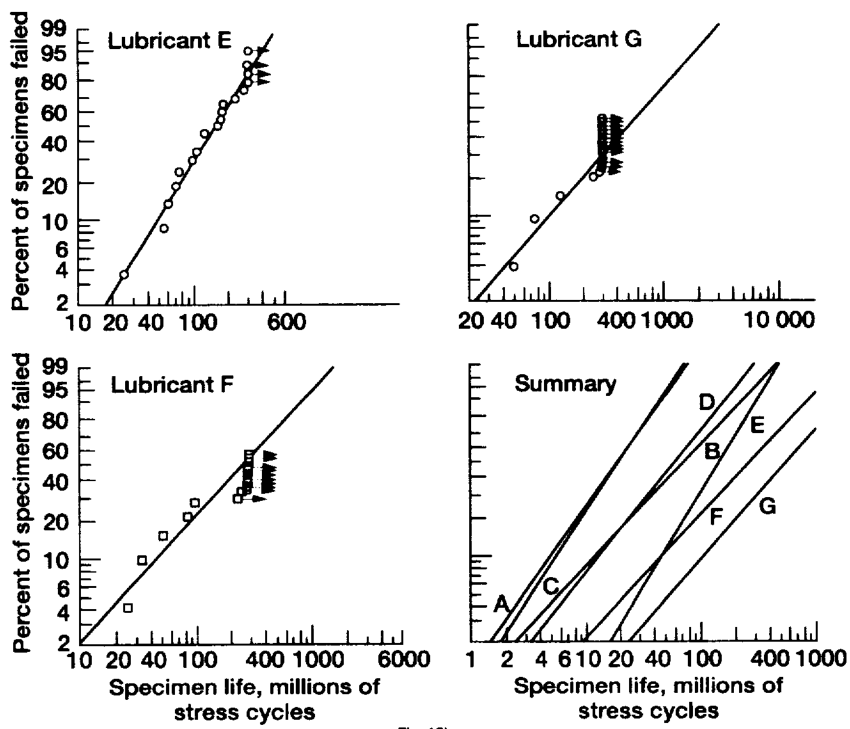



Fig. 15b

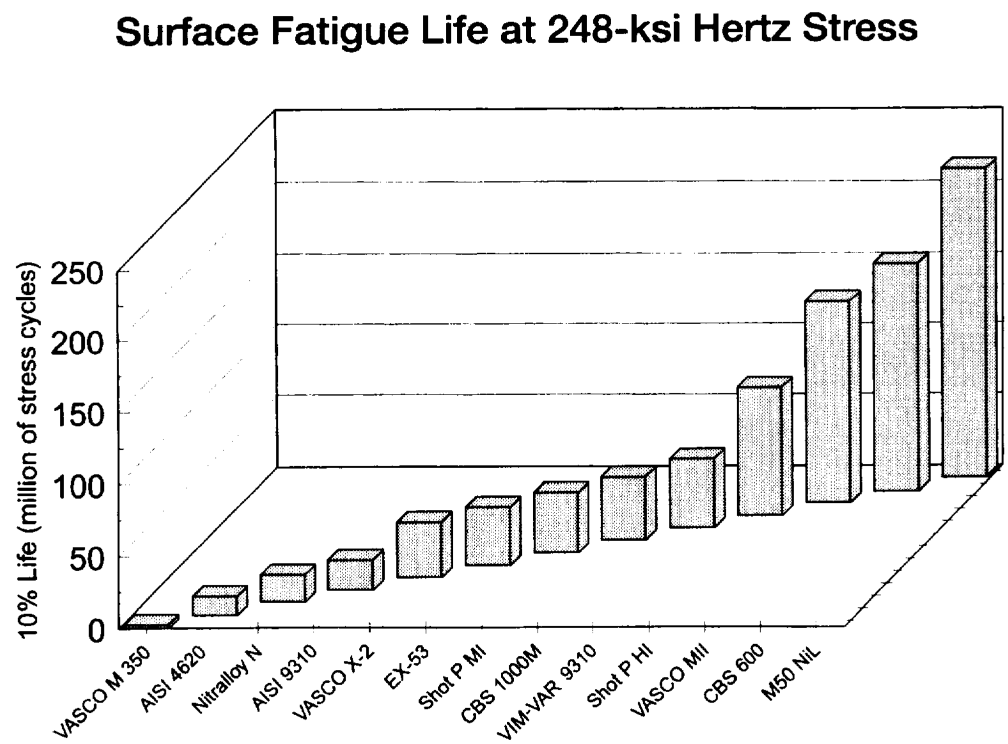

Surface Fatigue Life at 248-ksi Hertz Stress
10% Life (million of stress cycles)
250
200
150
100
50
0
VASCO M 350
AISI 4620
Nitralloy N
AISI 9310
VASCO X-2
EX-53
Shot P MI
CBS 1000M
VIM-VAR 9310
Shot P HI
VASCO MII
CBS 600
M50 NiL

Fig. 16

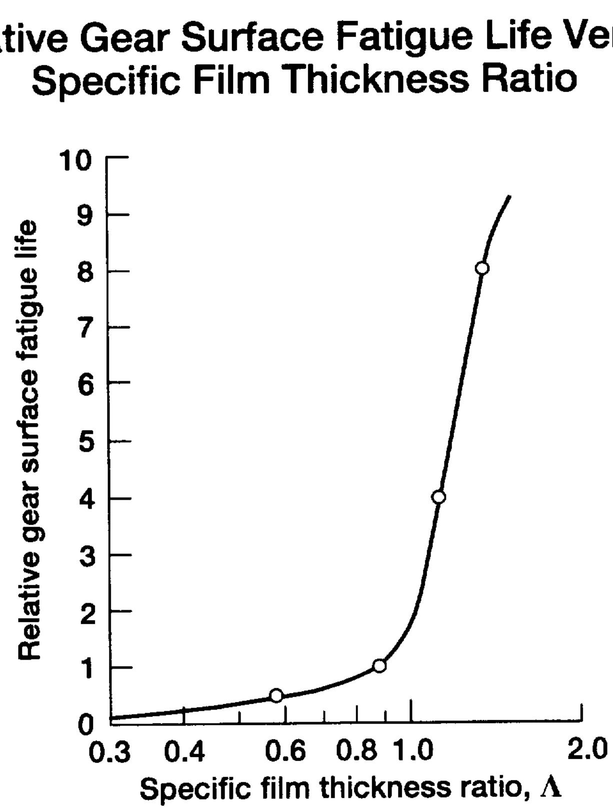

Relative Gear Surface Fatigue Life Versus Specific Film Thickness Ratio
Relative gear surface fatigue life
10
9
8
7
6
5
4
3
2
1
0
0.3 0.4 0.6 0.8 1.0 2.0
Specific film thickness ratio, Λ

Fig. 17